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Degradation study of heat exchangers

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Abstract

This study mainly deals with the evaluation of various degradation mechanisms that heat exchangers are susceptible to with an aim of evaluating future design requirements. A heat exchanger is a heat management system that uses fluids to transfer heat from one medium to the other; the most common types of fluids being air, water, oil or specialised coolant mixtures. As part of this study a failure analysis of heat exchangers was carried out on selected heat exchangers used in both aerospace and automotive sectors. This study was then extended to designing test-rigs supporting two types of heat exchangers. For this study, an air-to-air and an oil-to-air heat exchanger test rigs were designed. Temperature, pressure and flow sensors were introduced in the test rig designs to monitor the flow characteristics in order to determine if degradations occurring as a result of operation have an impact on them. As part of the initial evaluation both visual inspection and pulsed thermography inspection were selected as suitable inspection methods to evaluate their in-service condition. Some heat exchanger units where then subjected to accelerated corrosion tests and their performance was monitored using scanning electron microscopy (SEM) measurements. The outcomes of the study presented in this paper confirm the suitability and adaptability of thermography in detecting degradations occurring in heat exchangers.

Keywords: Degradation, Heat exchangers, Passive Thermography, Pulsed Thermography

1. Introduction

Heat transfer and fluid management systems are key parameters in the aerospace and automotive industry. Maintaining the working and performance of systems dealing with extreme temperatures, heat transfer systems play a pivotal role and hence their effective functioning is a prerequisite.

A heat exchanger is a system component which effectively and efficiently transfers heat from one medium to another. Usually, the fluids which pass through separated chambers, the walls of which act as a primary heat transfer surface. Within the flow chambers secondary heat transfer surfaces may also be present usually in the form of corrugated metals know as fins. A wide range of fluids can be used, the most popular ones being air, oil, water and coolant liquid [1]. Despite the wide use of these heat management units, manufacturers still struggle with failures occurring during service. They are mainly connected with temperature gradient, fouling and corrosion phenomenon.

Corrosion is the gradual and continuous degradation of metals and its alloys due to their exposure to harsh environmental conditions and their relative chemical reactions with some substances. As a result, it may generate pits on the surface, crevices and other localized damages. Simultaneous presence of corrosive fluids and tensile stress may lead to cracks and other degradations [1].

Non-destructive testing (NDT) has been in practice for quite a long time. The exploratory and mechanical progressions of the recent years has prompted the utilization of innovative procedures and instruments, for example, visual, x-radiography, colour penetrant testing, eddy current testing, ultrasonic testing and magnetic particle testing [2]. Thermography has been employed on the detection of failures heat exchangers. The main advantage of this technique against

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other NDT techniques remains in the very short inspection and analysis time.

2. The project

This paper presents ongoing work undertaken in the area of degradation assessment of aerospace grade heat exchangers. As the initial part of this study, common failures occurring in the heat exchangers, their mechanisms and their root causes were evaluated from literature. As the next stage of the project, static tests on the rate of corrosion and the detection of outer surface cracks using pulsed thermography were performed. With the available information from the literature and other existing research publications, two test-rigs, capable of testing air-to-air and oil-to-air heat exchangers were designed.

3. Types of failure

Failure is a physical indication indicating the poor performance of the system. Different types of heat exchanger failure have been analyzed based on literature studies and have been grouped according to the type of damage and its effect on the heat exchanger's characteristics, as follows:

- Crack and leak – one of the most dangerous failures caused by the separation of a material in two or more pieces due to the effect of stress [1].
- Blockage – a type of failure which is due to substance deposition on the pipe surface resulting in pipe blockage over time [1].
- Material removal – could occur due to material removal from the pipe surface due to the flow in the fluid resulting in cracks and leaks [1].

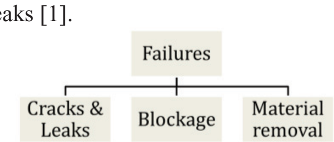

Fig. 1 Common failures occurring in heat exchangers

3.1. Failure Mechanisms

Failure mechanisms are the different processes which can lead a system to failure. Five major mechanisms exist;

- Fouling – the deposition of solid particles inside the pipes, causing reduction of their cross-section area eventually leading to blockage.
- Corrosion – the gradual destruction of the material surfaces by chemical reaction with their environment which leads to material removal [3].
- Erosion – mechanical abrasion of the material's surface which produces Total Dissolved Solids (TDS) in the fluid and leads to material removal [4].
- Fatigue – the structural damage of a material caused by repeated loading: thermal and mechanical stresses and leads to cracks and leaks.
- Vibration – a mechanical phenomenon which creates oscillations in the material at an equilibrium point. It leads to cracks and other mechanical fractures which can result in leaks or pressure drop changes.

3.2. Failure root causes

For the various mechanisms, root causes exist which lead to failure. The following are the root cause for the mechanisms mentioned previously.

3.2.1. Fouling – root causes

Fouling caused by dirt or other particles, creates scale formation on the heat exchanger surface. Consequences of this phenomenon can be very serious for heat transfer as it can result in decreased flux and increased temperature of the fluid that is supposed to be cooled [5].

Three types of root causes can be distinguished.

- Process parameters: Faster the flow rate, the smaller the probability of failure to occur; higher the pH, the harder it gets to control rate of heat transfer; high temperature of the cooled fluid disenables maintaining high process efficiency [6].
- Fouling phenomenon: To avoid failure, all manufactured components should be appropriately cleaned at the end of production process to reduce scaling risk. Even if the quality of the water doesn't suggest fouling risk, exaggerated amount of the same water cycles can be dangerous [5].
- Design parameters: The structure of the surface has an impact on the fouling process. Heat exchangers are designed mostly with enhanced inner surface to improve their thermal resistance and could accelerate the fouling process. Research shows that textured surfaces allow faster and easier scale formation than smooth ones [6]. What is more notable is that, not only is the velocity of fouling is different in case of smooth and enhanced surfaces; the level of fouling on the smooth surface is far less in comparison with its enhanced surface counterparts [7]. The appearances of dead areas also suggest bigger fouling risk, due to unimpeded flux inhibition [8].

3.2.2. Corrosion – root causes

The overall corrosion rate is determined by the fluid parameters. Some parameters that enhance the corrosion rate are: high temperature, low pH, high alkalinity, high conductivity, high rate of total dissolved solids (TDS), high hardness, low-pressure of wet steam, changes in flow regime, and high concentration of ions such as sulphate, nitrate, chloride, oxygen and iron. However, oxygen can sometimes have a protective role by creating a passive film, and its breakdown layer leads to pitting or crevice corrosion [9].

Elevated temperature leads to a lower rate of solubility of oxygen and hence the protective film is more likely to breakdown. A low pH reflects the presence of acid substances which are likely to attack and degrade the material rapidly. High alkalinity also has a similar effect.

Low-pressure of wet steam is one of the root causes for both uniform corrosion and erosion corrosion. This leads to breakdown of unalloyed steel. The flow medium causes a corrosive effect on the first baffle because of the water drops. The damage of protection layer reveals the blank steel which does not have sufficient corrosion resistance layer to avoid corrosion from wet steam [10].

An abrupt change in flow regime caused due to change in critical Reynolds number, from laminar to turbulent flow, also causes a rapid increase in corrosion rate. Turbulences can lead to cavitation which has catastrophic effects on corrosion. They can also enhance the transport of corrosive agents by mechanically tearing away corrosion products from the metal surface. An increase in the flow velocity facilitates oxygen transport, reduces the thickness of the Prandtl boundary layer and decreases the polarisation effects of particles which may react with the material [11].

3.2.3. Erosion –root causes

Erosion is a process that cannot be avoided. Some major factors are;

<u>*Total Dissolved Solids (TDS):*</u> the number TDS particles; sharp edges in the flow path, particle diameter, geometrical parameters and physical characteristics of the particles all affect erosion rate [9][11].

<u>*Fluid flow characteristics:*</u> the type of material in contact with the fluid, velocity of the fluid, impact angle [12][13]

<u>*Surface finish:*</u> the manufacturing process such as welding and water jet cutting, additive layer manufacturing, plasma laser powder welding could all add roughness to the finished surface of the heat exchanger [14][15]. Reducing the roughness can decrease the effective contact area; this implies a reduction in the erosion particle beam [15].

3.2.4. Fatigue – root causes

Four major root causes can lead to fatigue mechanisms.

<u>*Working parameters:*</u>

The first root cause represents the working parameters and is divided into two categories:

- Thermal overload
- Mechanical overstress.

In the first case, the material is subjected to a very high temperature and in the second case; it is subjected to very high stress.

<u>*Residual Stresses:*</u>

Residual stress can be generated due to manufacturing processes. For example, in the welding process materials undergo an increase in temperature and they re-appear during the solidification of the melted material due to plastic deformation [16][17]. With dissimilar materials, them having different expansion coefficient, thermal conductivity and melting point properties, the residual stress level is much higher. Nevertheless, residual stress can be reduced with adequate post processes such as post weld heat treatment (PWHT) [18].

Residual stresses also appear during the material processing such as bending and rolling. If an adequate post-heat treatment is not performed, they can lead to fracture [19].

Coating process can also have an important impact on residual stress (e.g.: shot-blasting).

<u>*Metallurgical Transformation:*</u>

The third root cause which can lead to fatigue is metallurgical transformation during the welding process. This is very critical when joining steels as they might undergo a microstructure change, leading to embrittlement of the material during transformation hardening (martensite/bainite) [16][17]. Moreover, the welding process can also have an impact on the grain size which might increase significantly.

<u>*Porosity / Microcracks:*</u>

The fourth root cause of fatigue is porosity/microcracks. The welding process itself leads to the formation of microcracks and porosity, taking place mainly in two areas: weld deposit and heat affected zone (HAZ). The former one can undergo hydrogen attack leading to cracking mainly in the centre line or in the interface of columnar grains resulting in gas entrapment during solidification [20]. On the other hand, if PWHT is not done properly, microcracks or even cracks can be created. This is referred to as reheat cracking. Moreover, lamellar tearing in the edge of the HAZ and cold cracking can occur during service life because of lower ductility after welding [20].

3.2.5. Vibration – root causes

Vibration is a failure mechanism that leads to crack formation and propagation as the component is unable to withstand the stress acting on it and leads to the removal of the material [21]. For example, destroying the protective film that keeps the material from corrosion, triggers localised corrosion [22]. Vibration triggers problems between elements that are next to each other and are localized in assembly zones such as tubesheets or baffles [22][23]. It is normally induced by two different situations;

1. The working environment of the heat exchanger.
2. The fluid flow conditions, for e.g., turbulent flow produces turbulent pressure pulsations inside the cavities [23].

4. Initial investigation techniques

As part of the initial experimental investigation, accelerated corrosion testing was carried out on metal coupons that form the core of oil-to-air heat exchanger. On the other hand, a pulsed thermography inspection was carried out on the air-to-air heat exchanger unit to determine degradations occurring on its outer shell.

4.1. Corrosion studies

Corrosion is one of the most likely degradations that occur in heat exchangers. As a scenario, it is more likely that salted solution in the form of moisture is flowing through the heat exchanger when the aircraft flies near the sea resulting in corrosion. In order to perform accelerated corrosion testing simulating the real life events, salted solution should be flown in the part and dried out. Exposure of such parts to moisture will then create a saturated solution and will corrode the part.

A study carried out by Stratmann et al [24] demonstrated that the maximum corrosion rate occurred at the limit between wet and dry atmospheres. If corrosion removes some material, the wall will be thin; hence the heat transfer is expected to be high. Alternately, when the salt forms an insulation layer, the heat transfer is expected to be low. However, it is worth noticing that the transitive layers on both sides (between the fluid and the metal sheet) might have a predominant effect on the reduction of wall thickness.

4.1.1. Accelerated corrosion test plan

For the current test, ammonium chloride was used to accelerate. The following is the test plan for accelerated corrosion test

- Degrease the as-received coupons and observe them using Scanning Electron Microscopy (SEM)
- Deposit a few crystals of ammonium chloride on several coupons and observe if it absorbs water, if not add three drops of water
- Leave it for ½ day, 1 day, 2 days and 4 days
- Wash off the salted solution from the coupon and preserve it in a desiccator chamber
- Observe corrosion with SEM

4.1.2. Results – Accelerated corrosion tests

The following are the initial results obtained from SEM.

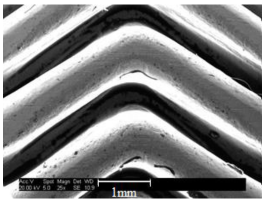

Fig. 2 SEM image at x25 mag – as received oil side coupon

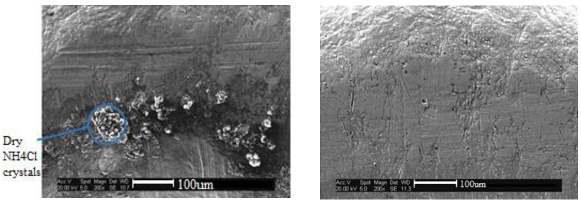

Fig. 3 Oil side coupon with corrosive solution at x200 mag after (left image) ½ day and (right image) 1 day exposure

Fig. 2 shows the SEM image of the as received oil side coupon taken at x25 magnification (mag) after preparing the sample as mentioned in the test plan. The left image as shown in Fig. 3 shows the deposition of ammonium chloride crystals prominently and do not show any indication of corrosion after ½ day exposure. The right image from Fig. 3 shows the SEM image obtained after 1 day exposure and does not show any visible signs of corrosion even at a magnification of x200. However, Fig. 4 shows clear signs of formation of blisters at a magnification of x25 (left image). When the magnification factor was increased to x1000 it was noticed that some blisters have now actually flaked off exposing the material to further corrosion.

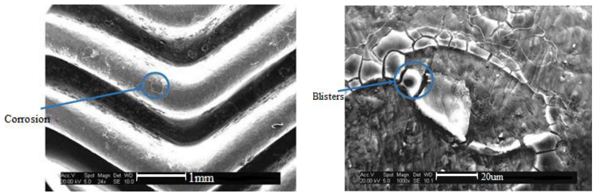

Fig. 4 Oil side coupon with corrosive solution after 2 days exposure (left image) at x25 mag and (right image) at x1000 mag

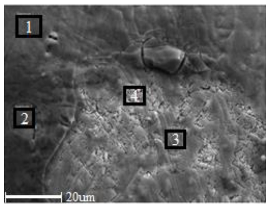

Fig. 5 SEM image of coupon (after 2days) showing various areas of the corroded part at x1000 mag.

Table 1Spectral analysis information of various corroded area as represented in Fig. 5. C-Carbon, O-Oxygen, Al-Aluminium, Mn-Manganese, Fe-Iron

Wt in %	C	O	Al	Mn	Fe	Total
Spectrum 1			99.3	0.7		100
Spectrum 2		4	95.2	0.8		100
Spectrum 3		1.8	97.6	0.6		100
Spectrum 4	4.5	4.7	89.2	1.1	0.5	100

In order to confirm that the features found are definitely products of corrosion, an elemental analysis was carried out. Table 1 above shows the various spectra represented by numbers on the SEM image, acquired from a 2 day exposed coupon (Fig.5). Spectrum 1 represents a sound area having only aluminium and manganese which forms the parent material composition. Spectrum 2 and 3 show the inclusion of oxygen onto the surface indicating the presence of an oxide film layer. However Spectrum 4 indicated the presence of carbon and iron which are products of corrosion, in addition to oxygen, aluminium and manganese confirming the onset of corrosion. These observations confirm that the parent material, made up of aluminium is no longer protected and is oxidised by ambient air confirming the occurrence of corrosion.

4.2. Pulsed thermography inspection

Thermography is a method which redefines the appearance of an object in the term of a surface temperature map [25]. It is a useful non-destructive testing (NDT) method as it is a non-contact technique; both small and large objects can be inspected; defects and damages occurring in components can be detected with a limitation to the depth location (few mm's) within seconds of external heat being applied. This method is widely used in many industries such as aerospace, automotive, manufacturing and construction [25].

In pulsed thermography technique, an external stimulus such as flash lamp or heat gun is used to induce the energy on to the surface of component over a short period of time. The infrared camera, which is controlled by a computer control unit, is used to record the response of emitted energy from the component as it cools. For a homogeneous material, a transient heat flow through an object is not interrupted and therefore the surface temperature shows an even cooling profile. As soon that the sub-surface feature appears along the diffusion path, the heat flow characteristic is changed. This break in transient heat flow shows up as hot spot or cold spot on the components surface temperature profile [26].

4.2.1. Experimental setup

Pulsed thermography was used to assess the health of the outer shell of the heat exchanger using the in-house system consisting of

1. Infrared (IR) Camera: FLIR 7600 IR camera which is a cooled, high-speed, quantum detector based, 640×512 pixel resolution, high speed camera
2. An integrated flash hood system comprising 2 flash lamps controlled by a capacitor bank unit
3. A computer control unit.

Fig. 6 Top-view of pulsed thermography experimental setup

4.2.2. Inspection – Working principle

The working principle of pulsed thermography has been mentioned in literature [25][26]. As mentioned above, flash lamps excite the sample surface with a short pulse which heats the surface of the component. The IR camera positioned perpendicular to the component surface records the surface cooling characteristics simultaneously. As the surface cools, any discontinuity appearing along the diffusion path will appear as a hot or a cold spot on the thermal image [25][26].

4.2.3. Results – Pulsed thermography inspection

The following is the initial result obtained from the pulsed thermography inspection.

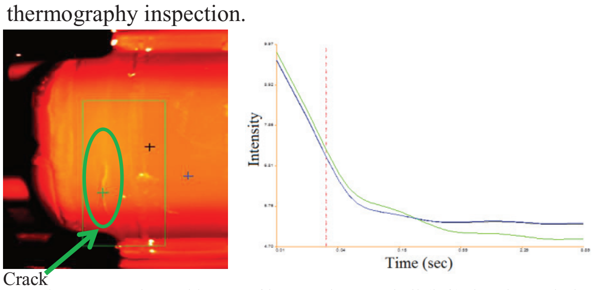

Fig. 7 RAW thermal image of heat exchanger shell (left), log thermal plot of the image on the left (right).

For initial test, several trials were undertaken as the heat exchanger was highly reflective in nature. To increase the surface emission characteristics, it was coated with a removable graphite spray. The above RAW thermal image (Fig.7 left) shows the areas that are sound (blue, black marker) and have damage (green marker). The black and blue curves show the sound area of the heat exchanger whereas the green marker shows the crack. It can be noted from the log thermal plot that the cooling characteristics of the damage is different confirming the presence of crack.

5. Proposed design of test rigs

Based on the available literature and the initial experimental results two separate rig designs were proposed.

5.1. Air-to-air rig design

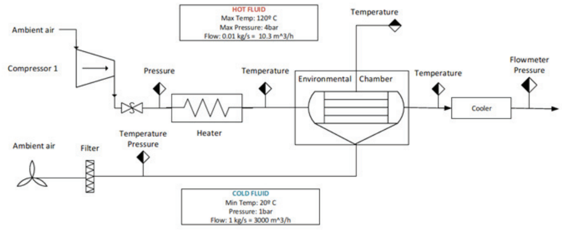

Fig. 8 Air-to-air rig design (proposed)

The rig for the air-to-air heat exchanger (Fig. 8) consists of a hot and a cold open circuit. The hot end of the rig starts with air being compressed by the compressor. Next, a heater raises the air temperature, now monitored by the temperature sensor before passing through the heat exchanger. At the exit of the heat exchanger, temperature is measured again to monitor its performance. A cooler will cool the exhaust to reduce it to acceptable limits before exhaust. Now for the cold end, a blower pushes ambient air through the filter to the heat exchanger and then sent to exhaust. It is anticipated that the performance of the heat exchanger will depend on its behaviour. The novelty in this setup is the introduction of the air-to-air heat exchanger into an environment test changer capable of simulating extreme temperatures thereby subjecting the unit to thermal cycling.

5.2. Oil-to-air rig design

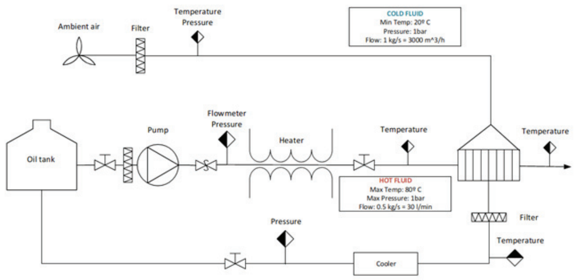

Fig. 9 Oil-to-air rig design (proposed)

The rig for the oil-to-air heat exchanger (Fig. 9) consists of a hot circuit (closed loop system) and a cold circuit (an open system). The hot one begins with an oil tank to store the fluid followed by a pump that takes it from the container and pushes it into the system through a filter. The oil then flows through the heater and its temperature before entering the heat exchanger is recorded. Temperature of the oil as it exits the heat exchanger is recorded as well before cooling it and sending it back to the oil tank. The cold air circuit remains the same as described in the air-to-air rig design.

5.3. Proposed tests

The ability to be able to perform degradation analysis of heat exchangers forms the central theme of the project. Two different rig designs (an air-to-air and oil-to-air) were proposed based on publicly available literature and initial test results. It is anticipated that these rigs will be physically built to monitor the performance of two types of heat exchangers as indicated in the design. It is anticipated that good working units will be subjected to accelerated corrosion and then introduced into the test rig. The performance will be monitored both from data obtained from passive thermography and from actual sensor measurement.

6. Conclusion

This paper presented the findings of research that is currently being untaken in the area of degradation and lifing assessment of heat exchangers. An analysis of most common failures and their mechanisms has been presented together with initial static tests comprising accelerated corrosion and pulsed thermography tests. Finally, two rig designs were proposed based on the available literature and initial static tests that will help monitor the performance of heat exchangers.

Future work: It should be noted that the work presented in this paper is a current research topic and will now move on to the next stage which will involve the physical construction of the rig and further degradation testing.

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References

[1] Shah, R. K. and Sekulic, D. P., (2003), “Fundamentals of heat exchanger design”, John Wiley & Sons, ISBN: 0-471-32171-0.
[2] Meier, H., Volker, O., Funke, B., “Industrial Produc-Service Systems (IPS2) – Paradigm shift by mutually determined products and services”, (2011), Int J Adv Manuf Technol, vol 52, pp. 1175-1191, DOI: 10.1007/s00170-010-2764-6.
[3] Akinpelumi, K. F., (2012), “To investigate the effect of pH on corrosion rate: a short laboratory report”, Chemical Engineering Laboratory II, University of Lagos.
[4] Deen, K. M., Virk, M. A., Haque, C. I., Ahmad, R. and Khan, I. H. (2010), "Failure investigation of heat exchanger plates due to pitting corrosion", Engineering Failure Analysis, vol. 17, no. 4, pp. 886-893.
[5] Demadis, K. D. (2003), "Combating heat exchanger fouling and corrosion phenomena in process waters", Compact Heat Exchangers and Enhancement Technology for the Process Industries, pp. 483-490.
[6] Kukulka, D. J. and Devgun, M. (2007), "Fluid temperature and velocity effect on fouling", Applied Thermal Engineering, vol. 27, no. 16 SPEC. ISS., pp. 2732-2744.
[7] Hays, G.F., Beardwood, E.S., Colby, S.J. (2005), "Enhanced heat exchnager tubes: their fouling tendency and potential cleanup", Proceedings of 6th International Conference on Heat Exchanger Fouling and Cleaning- Challanges and Opportunities, Kloster Irsee, Germany.
[8] Butterworth, D. (2002), "Design of shell-and-tube heat exchangers when the fouling depends on local temperature and velocity", Applied Thermal Engineering, Pergamon, pp. 789-801.
[9] Deen, K. M., Virk, M. A., Haque, C. I., Ahmad, R. and Khan, I. H. (2010), "Failure investigation of heat exchanger plates due to pitting corrosion", Engineering Failure Analysis, vol. 17, no. 4, pp. 886-893.
[10] Klein, U., Zunkel, A. and Eberle, A. (2014), "Breakdown of heat exchangers due to erosion corrosion and fretting caused by inappropriate operating conditions", Engineering Failure Analysis, vol. 43, pp. 271-280.
[11] Wojnar, W. (2013), "Erosion of heat exchangers due to sootblowing", Engineering Failure Analysis, vol. 33, pp. 473-489.
[12] Ranjbar, K. (2010), "Effect of flow induced corrosion and erosion on failure of a tubular heat exchanger", Materials and Design, vol. 31, no. 1, pp. 613-619.
[13] Kuznicka, B. (2009), "Erosion-corrosion of heat exchanger tubes", Engineering Failure Analysis, vol. 16, no. 7, pp. 2382-2387.
[14] Gurevich, E. L. and Gurevich, S. V. (2014), "Laser Induced Periodic Surface Structures induced by surface plasmons coupled via roughness", Applied Surface Science, vol. 302, pp. 118-123.
[15] Wang, D., Tian, Z., Shen, L., Liu, Z. and Huang, Y. (2014), "Effects of laser remelting on microstructure and solid particle erosion characteristics of ZrO2-7wt%Y2O3 thermal barrier coating prepared by plasma spraying", Ceramics International, vol. 40, no. 6, pp. 8791-8799.
[16] Otegui, J. L. and Fazzini, P. G. (2004), "Failure analysis of tube-tubesheet welds in cracked gas heat exchangers", Engineering Failure Analysis, vol. 11, no. 6, pp. 903-913.
[17] Missori, S., Costanza, G., Sili, A. and Tata, M. E. (2014), "Metallurgical modifications and residual stress in welded steel with average carbon content", Welding International, vol. 29, no. 2, pp. 124-130.
[18] Guo, C., Han, C. J., Tang, Y. M., Zuo, Y. and Lin, S. Z. (2011), "Failure analysis of welded 0Cr13Al tube bundle in a heat exchanger", Engineering Failure Analysis, vol. 18, no. 3, pp. 890-894.
[19] Shuaib, A. N., Duffuaa, O. M., Merah, N. and Al-Nassar, Y. (2011), "Residual stresses in roller expanded tube-tubesheet joints with large initial clearance and grooves", Journal of Pressure Vessel Technology, Transactions of the ASME, vol. 133, no. 5.
[20] Easterling, K. (1992), Introduction to the physical metallurgy of welding, Elsevier ed.
[21] Vincent, B. T., Hassan, M. A. and Rogers, R. J. (2009), "A Probabilistic Assessment Technique Applied to a Cracked Heat Exchanger Tube Subjected to Flow-Induced Vibration", Journal of Pressure Vessel Technology, Transactions of the ASME, vol. 131, no. 3.
[22] Shahrani, S. and Al-Subai, S. (2014), "Failure Analysis of Heat Exchanger Tubes", Journal of Failure Analysis and Prevention, vol. 14, no. 6, pp. 790-800.
[23] Zukauskas, A., Katinas, V., (1980), “Flow induced vibration in heat exchanger tube banks”, Proc of Symposium of Prac Exp with Flow Induced Vibrations, (eds Naudascher. E., Rockwell. D.,), Springer, New York, pp. 188-196.
[24] Stratmann, M., Streckel, H., (1990) “On the atmospheric corrosion of metals which are covered with thin electrolyte layers – I. verification of the experimental technique”, Corrosion Science, vol.30, No.6/*7, pp.681-696.
[25] Maldague X. P. V., Jones T. S., Kaplan H., Marinetti S. and Prystay M., (2001), “Chapter 2: Fundamentals of Infrared and Thermal Testing: Part 1. Principles of Infrared and Thermal Testing,” in Nondestructive Handbook, Infrared and Thermal Testing, Volume 3, X. Maldague technical ed., P. O. Moore ed., 3rd edition, Columbus, Ohio, ASNT Press, pp. 718.
[26] Shepard, S., (2007), “Flash Thermography of Aerospace Composites”. in IV Conferencia Panamericana de END. Buenos Aires.

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